Problems and Progress in Flare Fast Particle Diagnostics

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Abstract

Recent progress in the diagnosis of flare fast particles is critically discussed with the main emphasis on high resolution Hard X-Ray (HXR) data from RHESSI and coordinated data from other instruments. Spectacular new photon data findings are highlighted as are advances in theoretical aspects of their use as fast particle diagnostics, and some important comparisons made with interplanetary particle data. More specifically the following topics are addressed

(a) RHESSI data on HXR (electron) versus gamma-ray line (ion) source locations.

(b) RHESSI hard X-ray source spatial structure in relation to theoretical models and loop density structure.

(c) Energy budget of flare electrons and the Neupert effect.

(d) Spectral deconvolution methods including blind target testing and results for RHESSI HXR spectra, including the reality and implications of dips inferred in electron spectra

(e) The relation between flare in-situ and interplanetary particle data.

Key words: Sun, Solar Flares, X-rays, Radio Emission, Energetic Particles

1   INTRODUCTION

We were invited to present a critical review of the present state of diagnostic methods for energetic particles in flares in the light of recent progress. To deal with all energy ranges of ions and electrons and all the numerous diagnostic techniques (Table 1) used for them is impossible in a 30-minute talk and a

short report like this, and we have concentrated almost exclusively on hard X-ray diagnostics of electrons but with mention of some other regimes. From other talks at this meeting, it was clear that we have not yet taken fully on board the more definitive objective testing of models which state of the art data now allow. For example strong possibilities now exist of exploring quantitatively the possible non-isothermality of ultra-hot thermal flare plasmas by means of HXR spectra (Brown, 1974), rather than sticking to an isothermal fit, with potentially major implications for estimates of the flare electron energy budget. So a critical review is timely, especially in the light of recent high quality data (especially the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (Lin et al., 2002)) which is truly designed to help unravel ambiguities in data interpretation.

It is useful to start by commenting on what we mean by "fast" particles. Hard X-rays (HXR) are, broadly speaking, those at energies above the atomic line regime - roughly 10 keV. Such photons can very well be emitted profusely by a very hot $(T >> 10^7 K)$ flare plasma so in the HXR sense these locally Maxwellian electrons are "fast", particularly in the Maxwellian tail. What we implicitly mean by "fast" particle, however, is particles of energy exceeding thermal ones. Thus, these particles are essentially not in a Maxwellian and are far from equilibrium and their distribution function can be arbitrary. Such particles are truly "non-thermal". It has to be noted, however, that the relevant mean free path of the particles may not be the collisional one - wave interactions can drive distributions toward some local steady distribution possibly, though not necessarily, Maxwellian. Thus the fact that a loop is longer than the mean free path of a (say) 50 keV particle does not preclude that particle being part of a locally near-Maxwellian distribution. On the other hand, seemingly non-Maxwellian distributions can be a sum of locally Maxwellian distributions.

We should also comment on why fast particles are important in flare modelling. While interpreting the HXR spectral diagnostic alone remains rather ambiguous, when combined with spatial and temporal HXR data and data at other wavelengths the data seem to be broadly consistent with a large fraction of flare impulsive phase power being in electrons of ≥ 20 keV and ions in the 0.1 - 1 MeV range. Fast particles may thus be vital in flare energy transport in that phase (There are clear indications that pre-heating and gradual phase heating must be by other mechanisms). Secondly, dissipation of 100 Gauss worth of magnetic energy in a coronal plasma of density $10^{10} cm^{-3}$ delivers a mean energy of 25 keV per particle. Such particles have collisional mean free paths vastly larger than current sheet thickness. Consequently reconnection theory cannot be wholly credible if it treats the plasma as a fluid (MHD) and ignores particle kinetics and/or the presence of waves.

Remote radiation measurements in principle comprise the set of Stokes In-

Electromagnetic radiation from particles:
X-ray Bremsstrahlung from electrons,
Plasma waves, gyrosynchrotron,
free-free radio emission,
nuclear and annihilation γ-ray lines,
pion decay γ-ray component,
atomic collision diagnostics, nonthermal ionisation, Hα impact polarization
Interplanetary Particles:
electrons, ions, neutrons

Table 1
The various particle diagnostics involved in flare studies

tensities $I_{O,Q,U,V}(\lambda, \mathbf{\Omega}, t)$ as functions of wavelength λ, line of sight direction $\mathbf{\Omega}$, and time t. The spatial information on $f_{e,i}(\mathbf{p}, \mathbf{r}, t)$ inferable is limited by the line of sight projection/integration in each pixel ($\mathbf{\Omega}$) and by the fact that many physically important scales (sheet thickness, gyroradii, Debye length) are well below any spatial resolution currently, or ever likely to be, attainable.

2 RESULTS FROM RHESSI AND RELATED DATA

2.1 Structure of Paper

The last decade or so has brought a vast wealth of new flare solar activity data (GRO Compton, YohKoh, SOHO, TRACE, RHESSI, WIND, CORONAS-F) over numerous energy ranges. Of these the most pertinent to progress in fast particle diagnostics in flares are the remote sensing high resolution HXR imaging spectrometry of RHESSI and the interplanetary data from WIND (cf. papers in Lin and Krucker at this meeting). In this Section we summarise some of the most exciting imaging results from RHESSI. In Section 3 we discuss in more detail the analysis of RHESSI spectra and in Section 4 we touch briefly on other data.

2.2 HXR versus Gamma-Ray Source Location.

Gamma-ray events detected by RHESSI have been few in number but offer some tantalising results for particle acceleration, some contrasting with expectations. In particular the July 23 2003 2.2 MeV gamma-ray line image
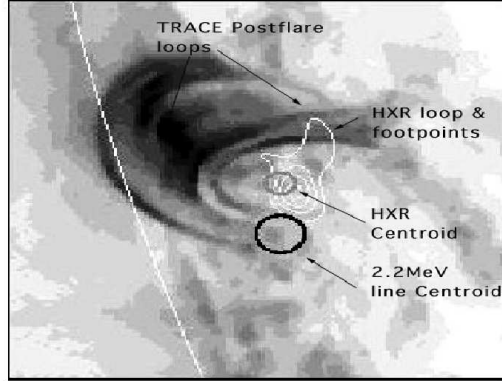
Fig. 1. Hard X-ray emission versus 2.2 MeV centroid location for July 23,2002 flare from Hurford et al., (2003).

(Hurford et al., 2003) has a centroid clearly separated from the centroid, or any part of, the HXR (300-500 keV) image (Figure 1). This appears to indicate that, in this event at least, MeV ions and deka-keV electrons are accelerated and/or propagate in different parts of the magnetic structure. As yet the only quantitative interpretation offered is that by Emslie, Miller and Brown (2004) in which ions are preferentially accelerated in larger structures than are electrons, or more generally in structures with longer Alfven travel times (i.e. structures of greater size, greater density, or lower field). The model can also yield the correct order of accelerated fluxes and spectra but only insofar as a suitable wave power is assumed.

2.3 RHESSI HXR Images - Morphology, spectral structure and evolution

Fully reliable methods for reconstruction of spectrometric images from RHESSI data are still under development but a variety of important new results have already emerged (Emslie et al., 2003). Though some HXR images show considerably more complexity than the canonical "two bright footpoints and faint coronal source", the majority of RHESSI images, of sources large enough to be resolved, do conform to that stereotype, at least approximately. Indeed, in high resolution spectrometric images at progressively higher energies (Aschwanden et al., 2002) show source separation from soft looptop to hard footpoints in line with the Brown (1971) thick target picture (The higher energy electrons penetrate deeper into solar atmosphere and thus produce higher energy X-ray emission in the region of higher density). The spectral index difference between footpoints can be roughly understood in terms of different column depth (Emslie et al., 2003). Aschwanden et al. (2002) have proposed that the loop density structure implied by these data, on the assumption of collisional transport, can be used as an atmospheric density probe.
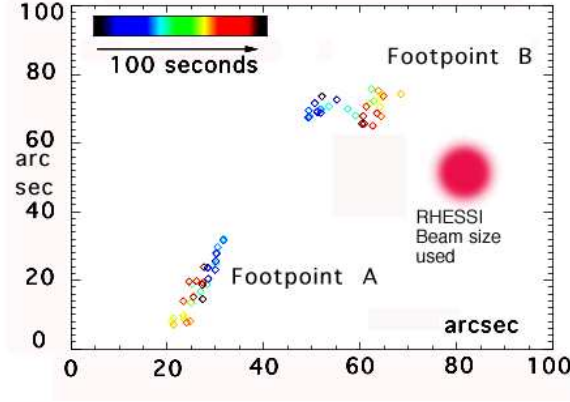
Fig. 2. Hard X-ray footpoint motion from Fletcher and Hudson (2002).

Fletcher and Hudson (2002) made a detailed study of HXR footpoint motion, arguing that it rules out a single monolithic loop structure throughout the event and suggesting that the source may instead comprise a progressively activated sequence of very small sources indicating the instantaneous bundle of field lines along which electrons are being accelerated (Figure 2). Since the HXR flux defines the total electron injection rate, this bundle cannot be too small ($>>$ current sheet thickness) or there would not be enough electrons available even if all of them were accelerated.

Dense thick target loop sources have been reported (Kosugi et al., 1994; Veronig and Brown, 2004) in which there are essentially no HXR footpoints, the entire loop emitting in both hard and soft XRs (Figure 3). The high SXR loop emission measure indicates a loop density high enough to stop all but the highest energy (≥ 50 keV) electrons. Such a scenario had in fact been hinted at earlier (Kosugi et al, 1994) for a YohKoh event.

Veronig et al. (2004) have studied the evolution of loop densities and temperatures and of HXR thick target beam parameters to test the physics of the Neupert effect (Neupert, 1969), interpreted purely as fast electron heating of loops. They find that including energy loss processes and comparing beam/plasma power gives a generally poorer cross-correlation than the raw Neupert HXR flux and time derivative of the SXR flux. They discuss possible interpretations of this paradox in terms of variable low energy cut-off, and of unresolved spatial structure including possible sequential activation of small field line bundles.

Kane and Hurford (2003) have reported a number of sustained coronal HXR sources of surprisingly large brightness and altitude but as yet no physical interpretation has been offered. These pose tantalising questions as to what field structure can accelerate and contain fast electrons in the corona.

While more work requires to be done, there are indications (Schmahl and Hur-
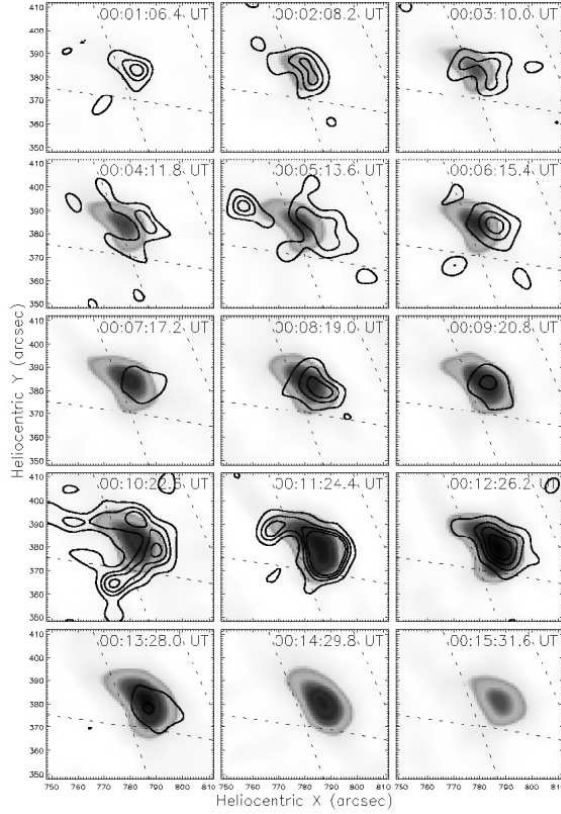
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Fig. 3. April 14 flare. RHESSI images from Veronig et al. (2004).

ford, 2002) that RHESSI images also contain information on the photospheric albedo patch around primary sources, with the possibility of source height inference (Brown, van Beek and McClymont 1975).

3   HXR SPECTRAL INVERSIONS AND SOURCE ELECTRON SPECTRA

As far as whole source HXR spectra are concerned (Figure 4) shows how far RHESSI has advanced over typical previous data, with photon spectral resolution of ~ 1 keV. These enable for the first time (apart from Lin and Schwartz 1984) the systematic inference of source electron spectra following Brown (1971) and subsequent refinements and numerical implementations (Johns and Lin (1992); Thompson et al. (1992); Piana et al. (2003); Kontar et al. (2004)) to allow for regularised noise suppression. Such inversions are now possible with such precision as to yield the mean source electron spectrum $\bar{F}(E)$ and local electron spectral index $\delta(E)$ as detailed functions of electron energy E (Figure 5). RHESSI data inversions of this kind are revealing a range of very interesting electron spectral features including variable high energy cut-offs (Kontar et al., 2004) and especially "dips" in the spectrum where $\delta(E)$ be-
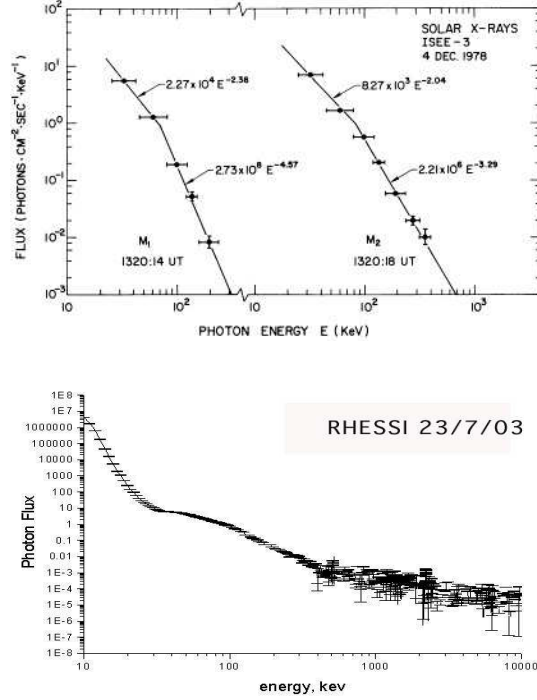
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Fig. 4. X-ray spectrum from 80s (Kane, Benz and Treumann, 1982) and RHESSI spectrum

comes very small or even negative (Figure 6)(Kontar and Brown, 2004). If such dips are proven to exist in the primary HXR spectrum they rule out a purely collisional thick target model in which the source electron spectrum cannot have $\delta(E) < -1$ (Kontar and Brown, 2004). Two possibilities that might make these inferred dips spurious are detector pulse pile-up (Smith et al., 2002) and albedo contributions (Alexander and Brown, 2002; Kontar, MacKinnon and Brown, 2004). Work so far appears to rule out pile-up but shows that albedo can create a spurious dip but at around 40 keV. In at least one case, shown in Figure 7, the dip is around 50 keV and so may be real, though primary source directivity has yet to be folded into the analysis. A genuine dip could be the first direct inference of a low energy break in the electron spectrum, crucial to the electron energy budget (Brown, 1971).

Given how vital the correct electron spectral shape is to testing models, Brown et al. (2004) are carrying out systematic tests of the reliabilities of different spectral inversion algorithms. One example of such a test is shown in Fig 8, which contains the (blind) target spectrum and the results of three distinct inversion algorithms, plus a forward best fit. Among the notable conclusions are that all the inversion algorithms are good at recovering dips and bumps, but that they do very badly in regimes where the electron flux is small (since high energy electrons swamp the photon data). These results are solely for an isotropic cross-section. Generally, results are quite sensitive to the exact form of the cross-section and so to the anisotropy of the electron distribution
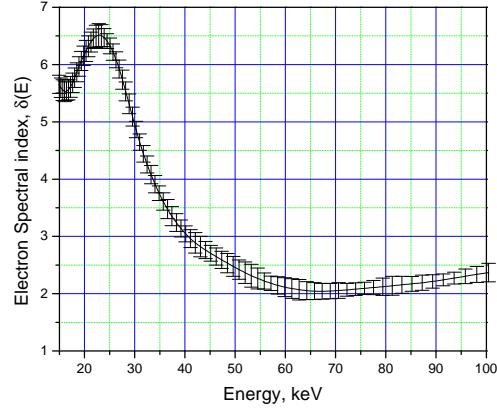
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Fig. 5. Variation of local electron spectral index for Aug 21, 2002 M-class flare from Kontar and MacKinnon (2005).
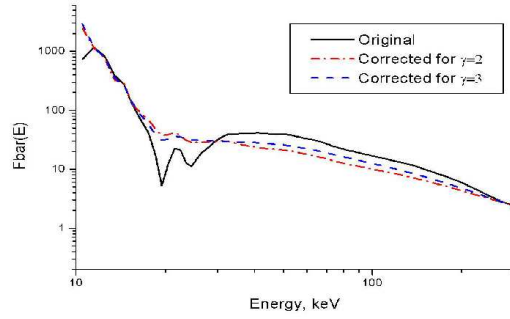

Fig. 6. Albedo correction and "dip" in mean electron spectrum for August 20, 2002 solar flare from Kontar et al. (2004).
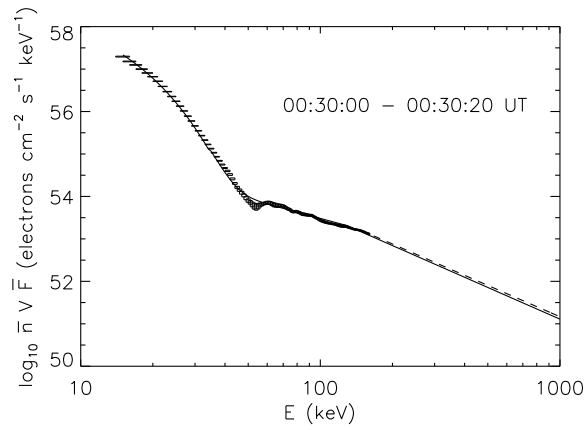

Fig. 7. Mean electron spectrum obtained for July 23, 2002 flare from Piana et al. (2003).
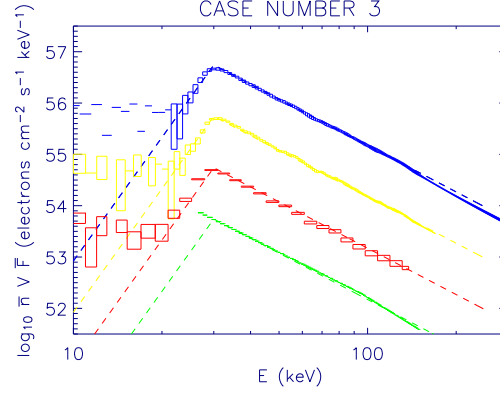
Fig. 8. The results of the inversions using various methods. Zero order regularization, first order regularization, regularization by coarse binning and forward fitting, respectively from top to bottom. The dash line shows the true solution. Successive curves have been scaled by 10 to render them visible.

(Massone et al., 2004). This situation is not as discouraging as might first be thought. Massone (2004) have shown that, at least in principle, bremsstrahlung spectra could contain some information on both the angular and energy distribution of the course electrons, analogously to the case of gyrosynchrotron spectra (Fleischmann and Melnikov, 2003).

These "mean source electron spectra" (Brown, Emslie and Kontar, 2003) are source model independent. Recently developed algorithms for inferring mean source electron spectra (Kontar et al., 2004a) show substantial variation of the spectral shape of the electron spectrum as flares evolve (Kontar et al., 2004b). Application of this technique to a flare on February 26, 2002 has shown that the maximum accelerated electron energy rises and falls with time after the peak of the event, concurrent with a growing low-energy thermal component of the hard X-ray emission (Figure 9) (Kontar et al., 2004b).

Assuming propagation is dominated by collisions, one can infer injected (accelerated) electron spectra. To infer these "injection" electron spectrum creating them is more uncertain than finding mean spectra, requiring second deconvolution (Brown and Emslie, 1988; Kontar et al., 2004b) and model assumptions such as target ionisation structure (Kontar et al., 2003), non-collisional energy losses (Zharkova and Gordovskyy, 2003) (Figure 10) and magnetic effects (e.g. mirroring) an electron propagation.

Tests for pure thermality of the source spectrum (i.e. superposition of Maxwellian) are also being developed but require high order data derivatives (Brown and Emslie, 1988).

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4 INTERPLANETARY PARTICLES

These have been discussed extensively by others at this meeting and here we mention only a couple of points in relation to remotely sensed data. The simultaneous operation of RHESSI, and of TRACE, SOHO, GRO and KO-RONAS, with the interplanetary particle and plasma probes aboard the WIND spacecraft is yielding many new insights. In particular the multi-made movies generated by Krucker (2003) showing RHESSI SXR and HXR image evolution superposed on TRACE images of near simultaneous EUV "jets" formed and associated with Type III bursts and interplanetary electrons give clues to where the acceleration action is. For example, the simultaneous upward and downward electron propagation places the acceleration region in between.

The outward propagating electron streams are clearly visible via their electromagnetic emission (Vilmer et al., 2003). WIND allows us to follow these electron streams below ionospheric frequency cut-off ($\sim$ 8MHz) down to the local space plasma frequency near the Earth orbit (20 kHz). For low energy electrons $\leq$ 50 keV collective effects are crucial, since freely streaming electrons build up unstable distribution functions. A recent self-consistent approach (Melnik, 1995) shows that the generation of Langmuir waves at the front of the stream, and absorption at the back, lead to low spatial dispersion of electrons (Kontar et al., 1998). These collective effects allow electrons to propagate without substantial energy loss and are a source of the high level of plasma turbulence required for Type III emission (Melnik and Kontar, 2000).

Krucker et al (2003) have studied the spectral indices (δ_{IP}) of interplanetary (IP) electrons in relation to that at the flare site implied by different models of the HXR source. They find the fascinating result (Krucker, Kontar and Lin, 2004) that δ_{IP} are much closer to the flare δ for accelerated electrons if the electrons produce their HXRs in a thin target rather than a collisionally thick one ($\delta_{THICK} = \delta_{THIN} + 2$) (Figure 11). This is strange, and correspondingly important. The possibility that HXRs are purely thin target is hard to reconcile with HXR footpoints and with the very large number of electrons it requires. An alternative explanation is that collective effects act on the beam (Haydock et al., 2001) to redistribute electron energies giving an effective energy loss cross-section which is constant with energy instead of $1/E^2$ for collisions alone. Wave-wave interaction brings additional complications and are sensitive to local plasma inhomogeneities (Kontar and Pecseli, 2002)
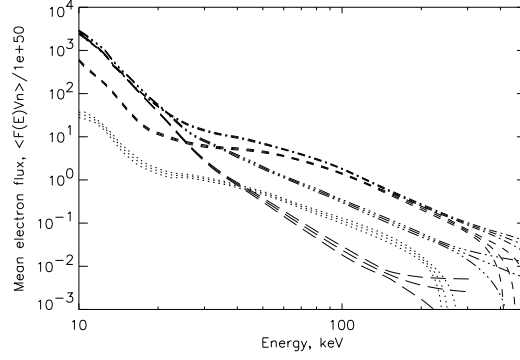
Fig. 9. High energy cut-off change for Feb 26, 2002 flare from Kontar et al. (2004b).
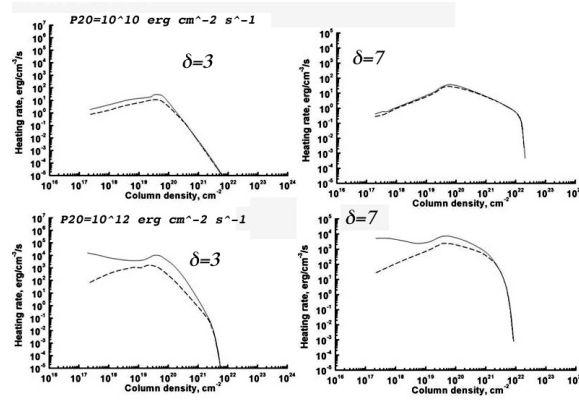

Fig. 10. Results of the simulations of beam propagation from Zharkova and Gordovskyy (2003).

5 CONCLUSIONS

The interpretation of remotely sensed data at all wavelengths continues to be riddled with ambiguities but the recent spate of high resolution data from RHESSI and the numerous coordinated observations from other instruments is truly starting to break down these barriers to the understanding of fast particle acceleration and propagation in flares.

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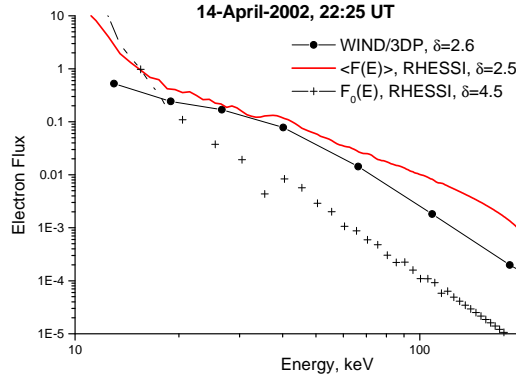
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Fig. 11. Comparison of X-ray emitting electron spectrum and in-situ electrons from Krucker et al (2004).

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